Electrical characterization of capacitively-coupled radio-frequency discharges in hydrogen

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Abstract

This work presents modeling and experimental results for the electrical characterization of capacitively-coupled radio-frequency discharges in hydrogen. A two-dimensional, time-dependent fluid model is used to describe the dynamics of electrons and positive ions H^+, H_2^+, and H_3^+at different frequencies (13.56–80 MHz), pressures (0.2–1 Torr), and rf applied voltages (50–800 V). The current-voltage relationship is reported and found in good qualitative agreement with experiment. The distribution, between electrons and ions, of the electrical power coupled to the plasma is analyzed. An investigation of the scaling laws for several important plasma parameters is also carried out.

Introduction

Capacitively-coupled radio-frequency discharges are routinely used in plasma-assisted material processing applications, and particularly in the plasma enhanced chemical vapor deposition (pecvd) of hydrogenated microcrystalline silicon (μ-Si:H) thin films, from a precursor mixture of SiH_4-H_2, under high dilution conditions for silane. The increasing demand for higher throughput, larger processing areas, improved uniformity and film quality in the semiconductor industry has motivated several modeling and experimental studies with the objective of optimizing this kind of discharges. This led to the identification of different scaling laws relating the various plasma parameters (electron density n_e, electron mean energy ε_e, sheath thickness s, discharge current I_rf, plasma potential V_p, self-bias voltage V_dc, ratio of the power lost in ion acceleration W_i to the power absorbed by electrons W_e) with the discharge operating conditions (rf applied voltage V_rf, excitation frequency f, gas pressure p, effective electrical power coupled to the plasma W_eff). These parameters are strongly coupled, thus justifying an analysis of their variations in order to meet processing requirements.

The experimental setup used here is similar to the GEC reference cell and it has been described in detail elsewhere.[1,2] The rf discharge is sustained between parallel plate electrodes (124 mm diameter and 30 mm inter-electrode distance), with the upper electrode (on which the rf voltage is measured) driven, and the lower electrode grounded. A grounded counter-electrode shields the back of the powered electrode, and the plasma is confined to the inter-electrode volume by a cylindrical grid fixed to the counter-electrode.

This work presents modeling and experimental results for the electrical characterization of capacitively-coupled radio-frequency discharges in hydrogen, for a wide range of operating conditions: f = 13.56-80 MHz, p = 0.2-1 Torr and V_rf = 50-800 V. The study uses a two-dimensional (2D) time-dependent fluid model that describes the production, transport, and destruction of electrons and positive ions H^+, H_2^+, and H_3^+. Calculation results obtained with this model are compared to experimental measurements for I_{rf} and W_{eff}, at various pressures, excitation frequencies, and rf applied voltages. The dependence of partial powers W_e and W_i on discharge operating conditions is also reported. Finally, the paper presents a summary of the scaling laws identified for the most important plasma parameters.

Model formulation

The model corresponds to a 2D time-dependent fluid description for electrons and H^+, H_2^+, and H_3^+ positive ions, which solves the continuity, momentum transfer and mean energy transport equations (the latter for electrons only), coupled with Poisson's equation. Boundary conditions involve symmetry considerations at reactor axis, and the imposition of the different particle and energy fluxes, together with the applied rf potential, at each physical boundary (electrodes, grid). Electron transport parameters are calculated adopting the local electron mean energy approximation.[3,4] The latter assumes that the space-time dependence of the electron energy distribution function and its related transport parameters (obtained by solving the homogeneous and stationary electron Boltzmann equation, written in the two-term approximation) proceeds via the electron mean energy profile, as obtained from the fluid code. The model adopts a simplified kinetic scheme for hydrogen, accounting for the main mechanisms of charged particle production and destruction, yet neglecting the kinetics and the transport of negative ions and neutral species. A detailed description of the model and its numerical solution can be found in Refs. 3-4.

Results and discussion

Figure 1 plots the current-voltage characteristics measured and calculated for a gas pressure p = 0.3 Torr and multiple excitation frequencies f = 13.56, 27.12 and 40.68 MHz. The current-voltage relationship exhibits a linear behavior, characteristic of electropositive discharges,[5] with the rf current scaling as $I_{rf} \sim V_{rf} f^{1.44}$ at constant pressure. The model underestimates I_{rf} measurements (note that calculation results are multiplied by a factor 10), which is probably associated with the fact that the present description neglects the coupling between the rf electrode and the counter-electrode. Note that, for the same rf current, the applied voltage is considerably smaller at high frequencies, which is due to the increase in the displacement current with frequency.

Figures 2 (a)-(c) represent, respectively, the total effective power coupled to the plasma (W_{eff}) and the partial power coupled to electrons (W_{e}) and ions (W_{i}), as a function of V_{rf}, for a pressure p = 0.3 Torr and different frequency values. The experimental measurements of W_{eff} were obtained using the subtractive method.[6] We observe a good agreement between model predictions and experimental measurements for W_{eff}, over a wide range of working conditions. Results show that both W_{e} and W_{i} increase with either V_{rf} or f, scaling as $W_{\mathrm{e}} \sim V_{\mathrm{rf}}^{\,1.2} f^{\,1.6}$ and $W_{\mathrm{i}} \sim V_{\mathrm{rf}}^{\,2.5} f^{\,1.6}$ at constant pressure, with W_{i} following a more rapid variation law on V_{rf}. Therefore, for pecvd applications, it is advantageous to operate at low applied voltages (regardless of frequency), in order to maximize the partial power absorbed by electrons while minimizing that transferred to the ions.

Figure 3 shows the partial power coupled to electrons (W_{e}) and ions (W_{i}), as a function of f, obtained at constant W_{eff} = 30 W and for a gas pressure p = 0.3 Torr. We observe that the power transferred to ions decreases with frequency, due to a reduction in the applied voltage, with the consequent increase of the power absorbed by electrons. Thus, the use of high excitation frequencies is of interest for applications, as it minimizes the ion energy at the electrodes while maintaining high deposition rates.

Figure 4 plots the ratio $W_{\mathrm{e}}/W_{\mathrm{i}}$, as a function of gas pressure, obtained at constant W_{eff} = 30 W and for different frequency values. The observed increase in $W_{\mathrm{e}}/W_{\mathrm{i}}$ with pressure is related to the reduction in the power transferred to ions due to a reduction in the electric field within the discharge, as pressure increases. Note that an increase in the excitation frequency reinforces the influence of a gas pressure variation.

A systematic study of the variation of other plasma parameters (electron density, electron mean energy, sheath thickness, discharge current, self-bias voltage, plasma potential, etc) with the rf applied voltage, the excitation frequency and the gas pressure, was presented in previous works.[4,7,8] Table 1 gives a summary of the scaling laws identified for several important plasma parameters, which are found to be qualitatively coherent with the results obtained in other models and simulations.[9,10]

Conclusion

This paper has presented the results for the electrical characterization of capacitively-coupled radio-frequency discharges in pure hydrogen, produced in a cylindrical parallel plate reactor similar to the GEC reference cell. A two-dimensional, time-dependent fluid model was used to describe the production, transport, and destruction of electrons and positive ions H^+, H_2^+, and H_3^+, for a wide range of operating conditions corresponding to f = 13.56-80 MHz, p = 0.2-1 Torr and V_{rf} = 50-800V. Good agreement was found for the current-voltage characteristic and for the effective electrical power coupled to the plasma at various frequencies and rf applied voltages. However, the values of the calculated rf current were a factor 10 below measurements, which may be due to an incomplete description of the reactor. Results showed that both W_e and W_i increase with either V_{rf} or f, at constant pressure. Therefore, it is advantageous to operate at low applied voltages (regardless of frequency), in order to maximize the partial power absorbed by electrons while minimizing that transferred to the ions. Moreover, W_e/W_i was found to vary linearly with p at constant W_{eff}, thus showing that an increase in pressure favors the transfer of power to electrons. The use of higher frequencies, at constant W_{eff}, reinforces the effect of a pressure increase. Finally, we have reported several scaling laws identified for the most important plasma parameters.

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Figure captions

Fig. 1: Current-voltage characteristics for a gas pressure p =0.3 Torr and the following excitation frequencies: 13.56 MHz (solid curve), 27.12 MHz (dashed), 40.68 MHz (dotted). The points correspond to experimental measurements obtained under the same discharge conditions at frequencies 13.56 MHz (squares), 27.12 MHz (circles), 40.68 MHz (triangles). The calculations are multiplied by a factor 10 for representation purposes.

Fig. 2: Electrical power coupled to the plasma as a function of the rf applied voltage, for discharges operating in the same conditions of fig 1. Total effective power (a), partial power absorbed by electrons (b), partial power transferred to ions (c). The points correspond to experimental measurements obtained under the same discharge conditions of fig 1.

Fig. 3: Electrical power coupled to electrons (solid curve) and ions (dashed), as a function of frequency, obtained at constant W_{eff} =30 W and for a gas pressure p =0.3 Torr.

Figure 4: Ratio of the power absorbed by electrons to the power lost in ion acceleration, as a function of gas pressure, obtained at constant W_{eff} = 30 W and for the following excitation frequencies: 13.56 MHz (solid curve), 27.12 MHz (dashed), 40.68 MHz (dotted).

Table 1 Scaling laws for plasma parameters

Scaling law	Conditions
$n_e \sim V_{rf} \cdot f^{1.6}$	p = 0.3 Torr
$V_p \sim V_{rf}$	p = 0.3 Torr
$V_{dc} \sim V_{rf} \cdot f^{0.13}$	p = 0.3 Torr
$s \sim V_{rf}^{0.08} \cdot f^{-0.48}$	p = 0.3 Torr
$I_{rf} \sim V_{rf} \cdot f^{1.44}$	p = 0.3 Torr
$W_{eff} \sim V_{rf}^{1.85} \cdot f^{1.6}$	p = 0.3 Torr
$W_e \sim V_{rf}^{1.2} \cdot f^{1.6}$	p = 0.3 Torr
$W_i \sim V_{rf}^{2.5} \cdot f^{1.6}$	p = 0.3 Torr
$n_e \sim f^{0.3}$	W_{eff} = 30 W, p = 0.3 Torr
$V_p \sim f^{-0.77}$	W_{eff} = 30 W, p = 0.3 Torr
$V_{dc} \sim f^{-0.89}$	W_{eff} = 30 W, p = 0.3 Torr
$s \sim f^{-0.44}$	W_{eff} = 30 W, p = 0.3 Torr
$W_e \sim f^{0.42}$	W_{eff} = 30 W, p = 0.3 Torr
$W_i \sim f^{-0.61}$	W_{eff} = 30 W, p = 0.3 Torr
$V_p \sim p^{-1} \cdot f^{0.06}$	V_{rf} = 100 V
$V_{dc} \sim p^{-1} \cdot f^{\beta}$, $0.22 \leq \beta(p) \leq -0.28$	V_{rf} = 100 V
$W_{eff} \sim p^{0.55} \cdot f^{1.6}$	V_{rf} = 100 V
$W_e/W_i \sim p \cdot f^{\beta}$, $0 \leq \beta(p) \leq -0.31$	V_{rf} = 100 V
$V_p \sim p^{-0.55}$	W_{eff} = 30 W
$V_{dc} \sim p^{-0.7}$	W_{eff} = 30 W
$s \sim p^{-0.35}$	W_{eff} = 30 W
$W_e \sim p^{0.4}$	W_{eff} = 30 W
$W_i \sim p^{-0.5}$	W_{eff} = 30 W

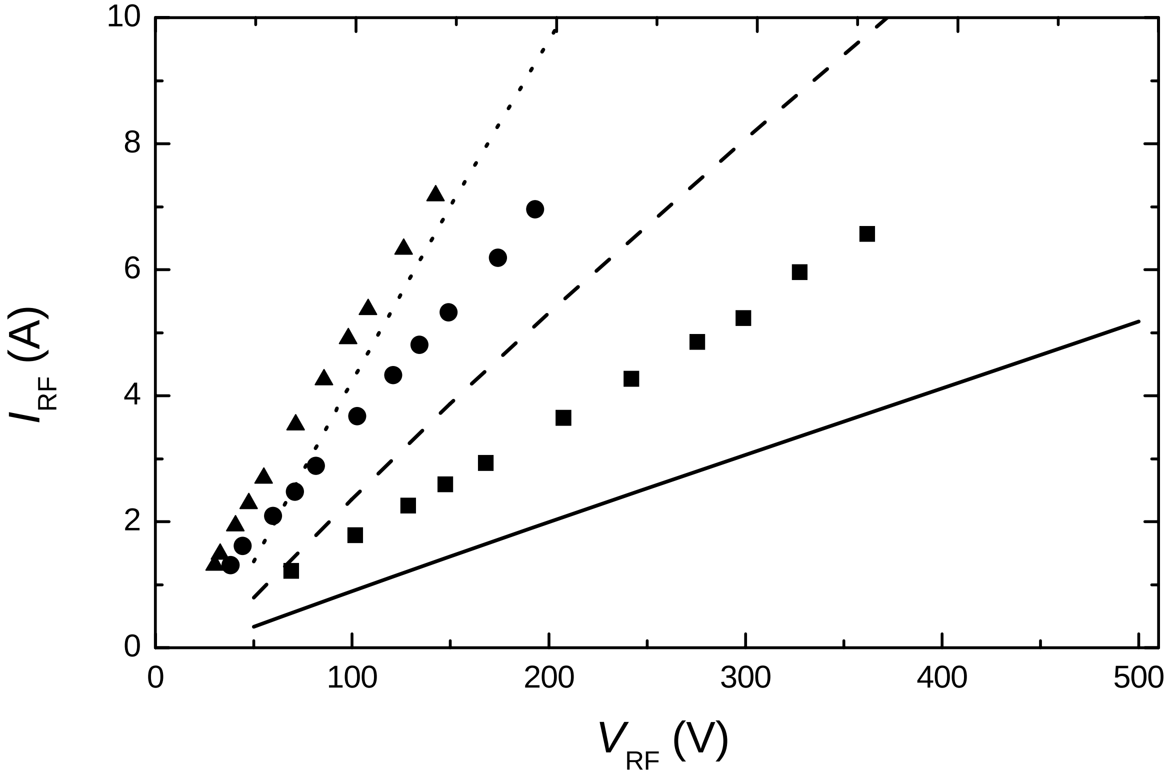

Fig. 1

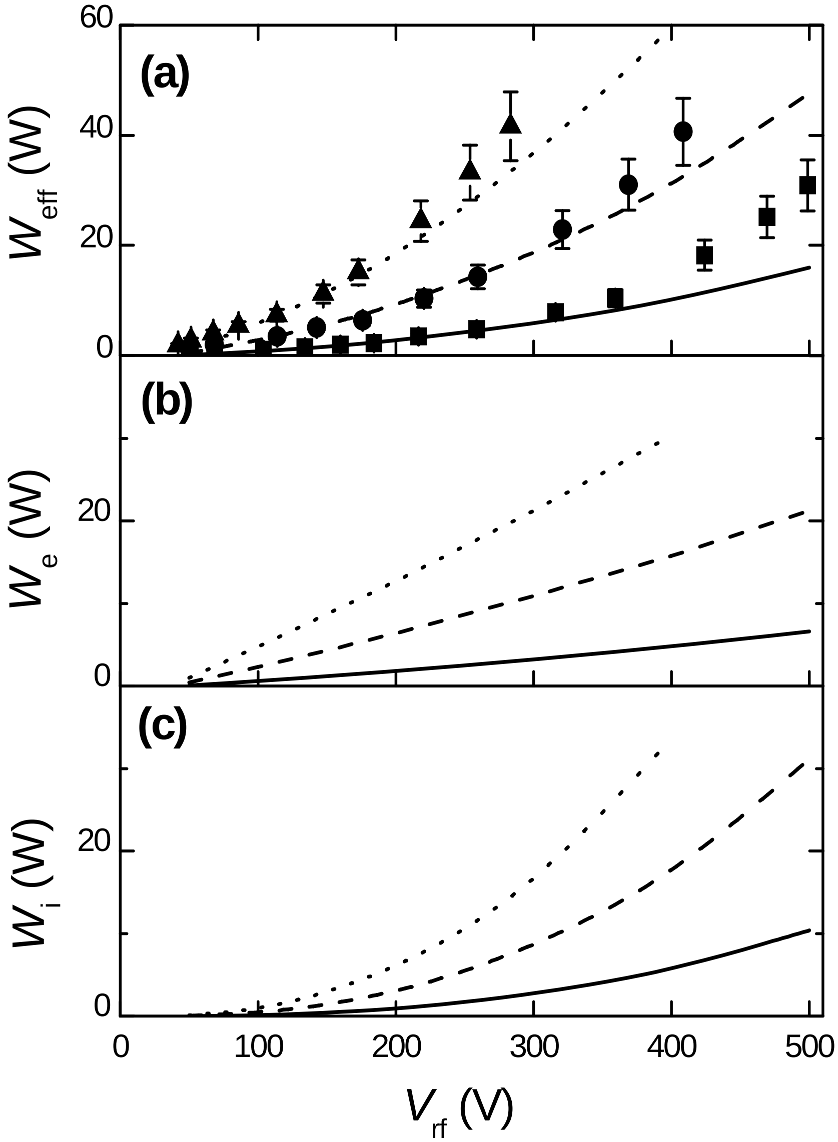

Fig 2

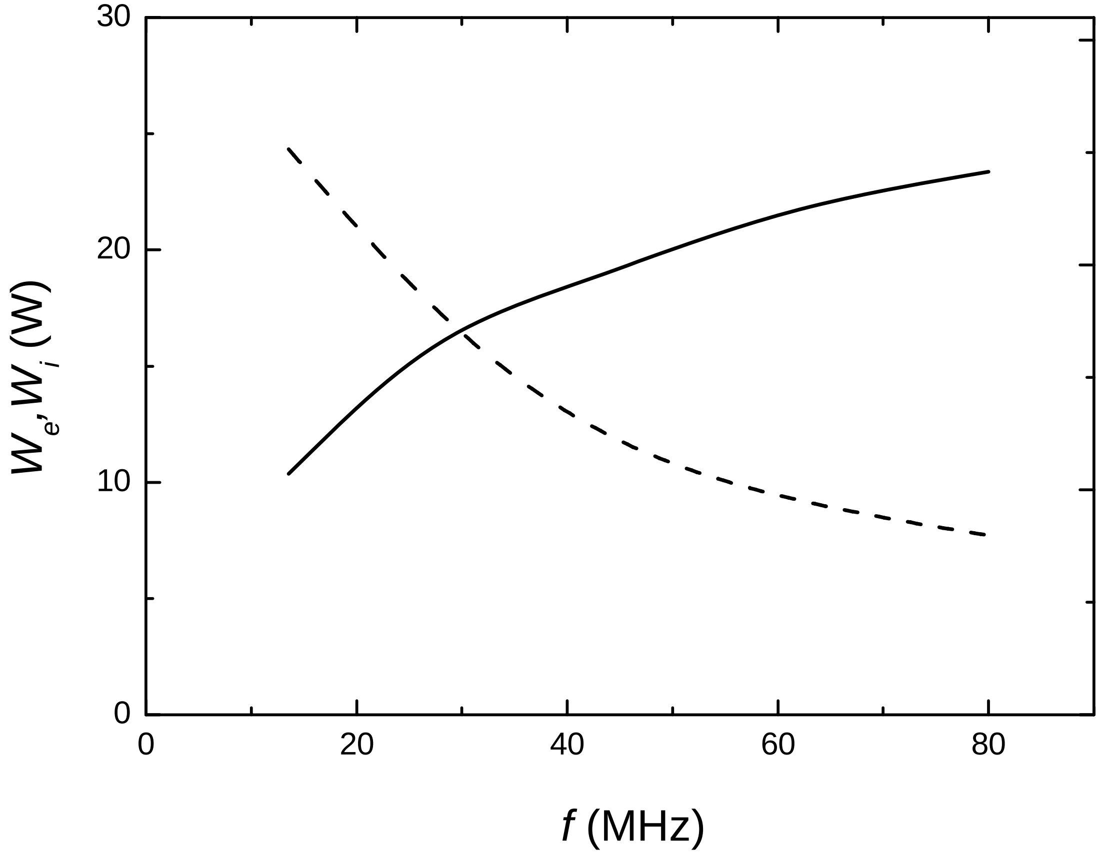

Fig 3

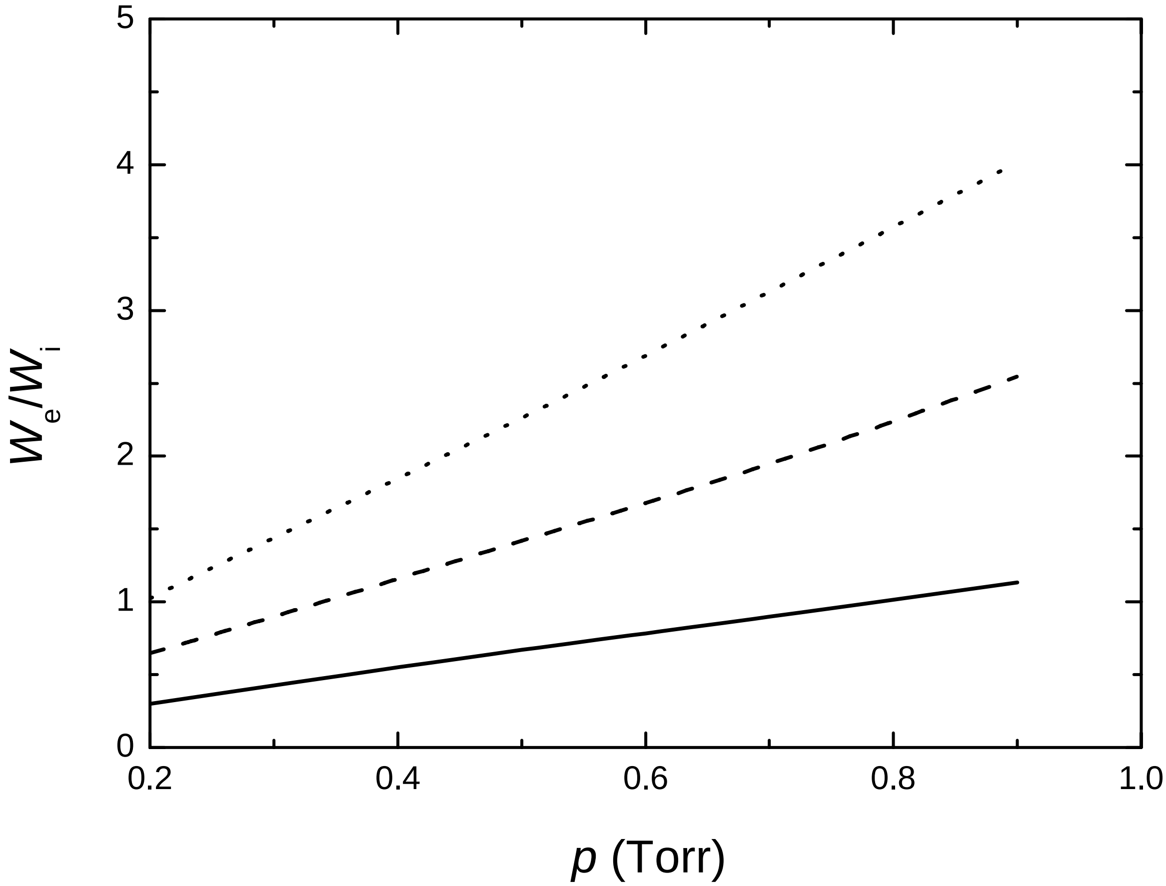

Fig 4

Text for table of contents

This work presents modeling and experimental results for the electrical characterization of capacitively-coupled radio-frequency discharges in hydrogen. We identified several scaling laws for plasma parameters, which can be of great utility in materials processing applications.